Title of Investigation:

Development of Kinetic Inductance X-ray Detectors for Large-Format Arrays (Extension)

Principal Investigator:

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Initiation Year:

FY 2004

Aggregate Amount of Funding Authorized in FY 2004 and Earlier Years:

$50,000

Funding Authorized for FY 2005:

Extension of 2004 funds into 2005

Actual or Expected Expenditure of FY 2005 Funding:

Contract: $15,000; Materials: $5,000

Status of Investigation at End of FY 2005:

Terminated at end of FY 2005. The investigation had been incomplete due to limited access to needed fabrication equipment.

Expected Completion Date:

December 31, 2005; later resumption possible under Constellation-X project

Purpose of Investigation:

The purpose of this investigation was to develop a next-generation X-ray imaging spectrometer with high-energy resolution. An imaging X-ray spectrometer makes an X-ray image of a portion of the sky. It breaks that portion into a number of picture elements ("pixels" for short). For each pixel, it gives the number of X-rays received as a function of X-ray energy. The challenges in building such an instrument are: (a) including a large number of pixels; (b) getting a precise energy distribution for each pixel; and (c) getting all that information out of the detector quickly. The state of the art in X-ray imaging is a 6 by 6 array (36 pixels) used in the Astro-E2 and a 32 by 32 (about 1000 pixels) array being developed for a new mission called Constellation-X. But the future of the field lies in technologies that can support mega-pixel arrays. This project is trying one new technology that might be able to do that. The technology involves measuring changes in the resistance properties of superconducting thin films.

More precisely, the new device would be a kinetic inductance detector. Such a detector would involve the microwave frequency measurement of the complex impedance of a thin superconducting film, and allow a simple frequency-domain approach to multiplexing. This results in a dramatic simplification of large detector arrays and associated cryogenic electronics, and harnesses the rapid advances in digital electronics for the wireless communications industry.

In a kinetic inductance detector, an X-ray is absorbed into a superconductor, breaking Cooper pairs into "quasi-particles"(qp) and phonons. These quasi-particles diffuse into the sensing element, which is a superconducting strip that forms part of an LCR resonant circuit. The quasi-particles change the kinetic inductance of the strip (changing the L), thus changing the frequency of the resonator's oscillation and its quality factor Q. By designing an array of detectors with different resonant frequencies, thousands of detectors could be read out through a single channel. Because these detectors are read out at microwave frequencies, they are referred to as microwave kinetic inductance detectors, or MKIDs.

In this DDF, our main goal has been to investigate materials chosen for the MKID and absorber. The energy gap in superconductors is $2\Delta \approx 3.5 k_B T_c$, where T_c is the superconducting transition temperature. Lower T_c materials will create more quasi-particles for a given photon, and thus will have a better statistical energy resolution. MKIDs at the Jet Propulsion Laboratory are currently made of aluminum, and the absorbers of tantalum. For the absorbers, we are researching other materials, like indium and tin, and for the MKID, aluminum as the material of first choice. However, our ultimate goal is to employ our tunable T_c Mo/Au bilayers, which we have been developing for the Constellation-X project. Mo/Au bilayers in principle could be made to maximize the energy resolution for a given design.

Accomplishments to Date:

We have designed, fabricated, and tested several test structures of aluminum MKIDs with indium absorbers. The fabrication was solely done at Goddard's Detector Development Laboratory (DDL). The detector characterization was performed at Caltech/JPL. Due to limited existing equipment and fabrication procedures, we had to temporarily abandon developing MKIDs with tin absorbers and focus only on indium absorbers.

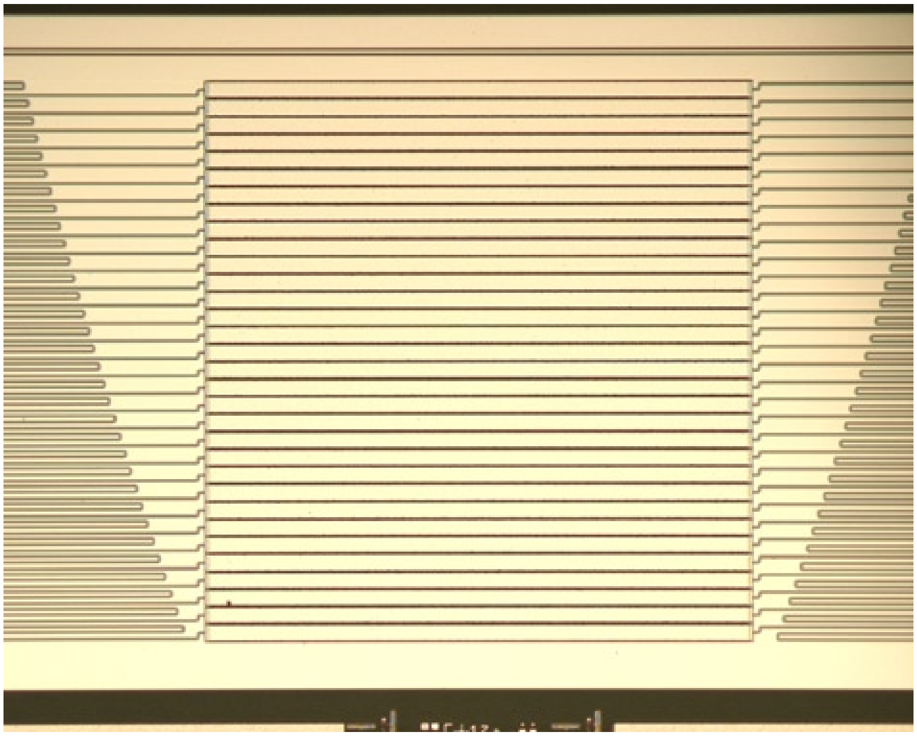

Figure 1. A complete 32-element indium strip array read out by aluminum resonators

Figure 1a shows an array of 32 MKIDs with indium strip absorbers. The 32 strip absorbers are 50 microns wide and 1.5 mm long. The pitch between the strips is less then 10 microns. Each absorber strip ends on an aluminum qp trapping area, which is part of the resonator. The gap between the center strip line and the ground plane of the resonator is only 2–3 microns wide. To reproducibly achieve this fine-line resolution, we had to drastically improve the standard procedure for optical photolithography using a contact printer.

MKID fabrication can be divided up into five steps: 1) Al sensor deposition and patterning, 2) producing a photo resist (PR) mask for metal lift-off, 3) surface ion-milling of the qp trapping areas through the PR mask, 4) indium absorber deposition, and 5) indium layer lift-off. The first step started with an electron-beam deposition of a 250 nm thick aluminum film on a 4-inch large HEMCOR single crystal sapphire (C-plane) wafer. To transfer the MKID sensor structure onto the aluminum film, a modified wet etch photolithography procedure was applied. Next, the wafer was PR recoated and the PR was patterned with the absorber layout. A special PR (MicroChem PMGI) was used to yield an overhanging PR edge profile, which was essential for our final metal lift-off step. Then, the wafer was loaded into a high-vacuum deposition chamber, where steps 3) and 4) were performed.

The most critical step in the MKID fabrication is cleaning the aluminum qp trapping areas through the open structures of the PR mask. Since aluminum had been exposed to various chemicals during the PR process, and since it had enough time to grow an aluminum oxide layer under ambient conditions, a more prolonged and aggressive cleaning step was needed using a standard ion-milling procedure. A thermal deposition of 500 nm of indium was performed shortly after the ion-milling process had been finished. After the indium deposition, the wafer was soaked for several hours in acetone for metal lift-off.

So far, detector analysis showed strong evidence that the quasi-particle trapping process was highly suppressed in our current MKIDs. Most likely, the interface area between the absorber and the aluminum sensor has not been transparent enough for quasi-particle diffusion, yet. Beyond the scope of this DDF project, we have been developing an improved cleaning process for the qp trapping areas to overcome the interface problem and to finally being able to use the potential benefits of MKIDs.

Planned Future Work:

Project may continue under Constellation-X funding.

Key Points Summary:

Project's innovative features: This technology has the potential for mega-pixel, high-energy resolution imaging arrays due to its straightforward multiplexing capabilities. The use of novel materials for the resonator circuits and the absorbers, combined with the absorber geometry, are all Goddard innovations to this research effort.

Potential payoff to Goddard/NASA: Several future X-ray observatories will require wide-field-of-view imaging spectrometers featuring high-energy resolution. Goddard is a world leader in X-ray detectors, and developing this new kinetic inductance technology will help ensure that Goddard continues as a major player in the X-ray detector field.

The criteria for success: The main criterion for success would be testing a functioning MKID detector fabricated at Goddard, preferably with a bridge absorber.

Technical risk factors: Unforeseen difficulties in depositing and characterizing the aluminum and tin films, as well as a longer-than-expected time for procuring the required lithographic masks to fabricate the devices, delayed our progress in this effort. A thicker-than-expected oxide film in the aluminum resonators prevented us from testing our first devices. We are now fabricating a Mo/Au resonator that should solve this problem. Our proposal has been extended into 2005 and we expect to produce working devices in the coming year.